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SAN JACINTO INTRUSIVE COMPLEX
3. CONSTRAINTS ON CRUSTAL MAGMA CHAMBER PROCESSES FROM STRONTIUM ISOTOPE HETEROGENEITY

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Abstract. Strontium isotope data from three large plutons interpreted as derived from dynamic magma chambers (Hill, this issue; Hill et al., this issue) show the existence of pronounced isotopic heterogeneity within each unit. Ranges of calculated initial $^{87}Sr/^{86}Sr$ are unit I, 0.7060-0.7076; unit II, 0.7060-0.7074; unit III, 0.7058-0.7073. A limited sample of mafic inclusions and dyke rocks, interpreted as samples of liquid added to the various chambers during inflation, have initial $^{87}Sr/^{86}Sr$ of 0.7068-0.7084. These variations are regular at the kilometer scale within each pluton and show no identified correlation with any other observed geochemical or petrological parameter. Slightly older small intrusions that span the compositional range olivine gabbro to granite show a systematic increase in initial $^{87}Sr/^{86}Sr$ from 0.7057 in the southwest to 0.7077 in the northeast, expressing the pattern previously reported for the northern 600 km of the Peninsular Ranges batholith. The Sr isotope data indicate that melt production, aggregation, transport, and crystallization processes were far from capable of completely homogenizing initial variations in initial $^{87}Sr/^{86}Sr$ within the liquids from which these rocks crystallized. Whole chamber convection is apparently ruled out by these data; more complex patterns, including double-diffusively induced horizontal stratification, are permitted.

Introduction

Many cogenetic igneous rock suites are interpreted to be related by complex processes that take place within high-level (crustal) magma chambers. Recent studies of both SiO_2-rich plutons and of zoned ash flow sheets inferred to have been erupted from the top of large SiO_2-rich crustal magma chambers demonstrate the complexities of the processes involved in the filling and solidification of such magma chambers [e.g., Bateman and Chappell, 1979; Hildreth, 1981]. Three recent developments in petrology are forcing reevaluation of models for the cooling and solidification of such large crustal magma chambers. Detailed reexamination of crystallization and solidification within the basaltic Skaergaard Intrusion has shown that the physical and rheological properties of magmas may be important controls on magma chamber processes [McBirney and Noyes, 1979]; fluid mechanical modeling is allowing quantification of the fluid dynamical effects of such properties as viscosity and thermal and chemical gradients [e.g., Huppert and Turner, 1981; Huppert et al., 1983]; and the arguments of O'Hara [1977, 1980] that magma chambers should be considered dynamic rather than static entities are in accord with both the fluid dynamical studies and with petrological and isotopic evidence for recharge within large layered intrusions [e.g., Irvine, 1980; Kruger and Marsh, 1982]. The scales over which these processes are important are poorly known. This paper presents strontium isotope data that allow constraints to be placed on the efficiency and scale of convective processes operating within several large relatively SiO_2-rich crustal magma chambers.

The demonstration of initial isotopic heterogeneity within individual intrusive units of the Murrumbidgee Batholith [Roddick and Compston, 1977] suggested that given favorable circumstances, isotope studies may be used to study the evolution of now solidified magma chambers. This study also suggested using isotope data to constrain possible mechanisms by which new liquid is added to a developing chamber. We have conducted a detailed geological, geochemical, and isotopic study of Cretaceous plutonic rocks exposed in the San Jacinto Mountains of southern California. These plutons and their igneous and metasedimentary wall rocks comprise the northeastern corner of the Cretaceous Peninsular Ranges batholith (PRB) [Silver et al., 1979]. The igneous rocks of the PRB show geographically consistent patterns in the distribution of many geochemical and isotopic parameters. From west to east across the batholith both the initial $^{87}Sr/^{86}Sr$ ratio (Sr_i) and $\delta^{18}O$ increase (0.703-0.708; +6.0-+13.0, respectively) [Early and Silver, 1973; Taylor and Silver, 1978], while initial $^{143}Nd/^{144}Nd$ decreases [DePaolo, 1981a]. Although major element characteristics show little, if any, west-to-east variation, trace element abundances and ratios may show substantial regional zonation approximately paralleling the isotope patterns [Silver and Early, 1977; Gromet and Silver, 1979; Silver et al., 1979].

The identification of these west-to-east variations prompted the question: "If a large pluton comprises 20% of the width of the batholith at a particular latitude, will it contain 20% of the cross-batholithic isotopic variation also?" Data gathered on the isotopic heterogeneity (or lack thereof) within a single, mappable igneous unit could then be used to constrain models of magma transport and magma chamber dynamics. Substantial isotopic heterogeneity within such a chamber would necessarily imply that mixing, by whatever processes, is not efficient or that the chamber was filled incrementally by batches of heterogeneous liquid. If convection is the dominant transport process within the magma chamber, this would further imply that the length scale for convection is small compared to the dimensions of the magma chamber, that the time scale for con-

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vection is large compared to the time scale for crystallization, or both. Such conclusions appear contrary to those obtained by theoretical analysis of simple systems [e.g., Shaw, 1965; Bartlett, 1969; Spera et al., 1982], but may be compatible with models in which more complex processes, such as boundary layer flow during sidewall crystallization or double-diffusive layering and recharge [e.g., McBirney, 1980; O'Hara and Matthews, 1981] are involved.

Our data from three large tonalite plutons show that the range in Sr_i within each pluton is relatively large and is comparable to that expected from the batholith scale variations. These data allow important inferences to be made about both the transport and solifidication of the silicate liquids involved in formation of these plutons.

Geology and Previous Work

The geology and geochemistry of the igneous rocks of the San Jacinto Mountains are described by Hill [this issue] and Hill et al. [this issue]; oxygen isotope data are reported elsewhere [Hill et al., 1986b]. A summary of these results has appeared previously [Hill et al., 1985]. Briefly, three large (>100 km²) tonalite plutons intrude small, slightly older compositionally variable (olivine gabbro to granite) igneous masses, as well as sequences of metasedimentary rocks that may be as old as late Precambrian [Hill and Silver, 1983]. The three large tonalite plutons are composed of relatively homogeneous tonalite consisting of plagioclase (An_{30-40})(50-55 vol %), quartz (20-30%), K-feldspar (1-8%), biotite (10-15%), hornblende (0-5%), titanite (0-2%), and accessory zircon, apatite, allanite, and ilmenite. Variations in mineral abundance are geographically consistent only within the eastern part of the youngest pluton, unit III, which grades from a mafic tonalite rim to a central K-feldspar-poor granodiorite. The three major plutons (units I, II, and III) were emplaced between 93 and 94 Ma; two early intrusives give dates of 97-99 Ma, implying rapid intrusion and solidification of the entire igneous construct (L.T. Silver et al., manuscript in preparation).

Synplutonic mafic dykes are abundant adjacent to inward dipping contacts within unit III. Mafic inclusions, common throughout the three major plutons, are interpreted to be derived from breakup of such dykes, and the dykes are interpreted as conduits through which liquids were injected into the growing magma chambers. A few tonalite dykes have been discriminated, and are interpreted as representing the conduits through which the bulk of the magma was injected into these plutons. Mineral and inclusion foliations and lineations, schlieren, and apparent scour and flow differentiation features are interpreted as evidence for repeated relative movement of materials within the magma chambers.

Eighty-five percent of analyzed samples have between 62.5 and 68.0 wt % SiO_2. Half the remaining samples are of volumetrically insignificant felsic differentiates that were collected to explore the effects of apparent extreme in situ differentiation. Mineral compositions show similar restricted ranges. The mean plagioclase composition falls from An_{40} in the most mafic tonalites to An_{30} in the most felsic granodiorites. The entire microprobe determined range is An_{44-27} and the range of Mg/(Mg+Fe) of mafic minerals is comparably limited.

The combined geological, mineralogical, and geochemical data are interpreted in terms of a dynamic magma chamber in which newly added melts were mixed with evolved liquids already present in the chamber. The dyke liquids added to the inflating magma chambers spanned a considerable compositional range, at least from quartz diorite to felsic tonalite, but were dominantly of tonalitic composition. Smaller compositional contrasts between added and resident liquids promoted more efficient mixing of the two. Injected liquids more mafic than mafic tonalite typically formed discrete mafic inclusions, whereas more felsic liquids apparently mixed completely with the tonalite liquids already resident in the chamber (bulk composition 66-67% SiO_2).

Oxygen isotope data provide confirmation of the presence of mixing, especially within the liquids that solidified to form the central, regularly varying rocks of unit III [Hill et al., 1986]. Mafic rocks from this and the other two plutons show a large variation in measured whole rock $\delta^{18}O$ values of from +9.0 to +10.5 ‰. Within the central rocks of unit III, $\delta^{18}O$ values vary systematically from +10.0 to +10.5 ‰. This variation appears to be entirely the result of different mineral proportions within samples, and it implies crystallization of much of this pluton from a liquid with an homogeneous $\delta^{18}O$ value of about 10.2 ± 0.2 ‰. The whole rock oxygen data do not allow resolution of small (~±0.1 ‰) differences in the oxygen isotopic composition of the liquids from which these rocks solidified, but they certainly appear to require considerable homogenization of the isotopically variable liquids (shown by the range of $\delta^{18}O$ values for the mafic tonalites) added to the chambers.

There is little field evidence for interaction between the igneous rocks and their metasedimentary wall rocks. Subsolidus (hydrothermal?) alteration appears to be of minor importance and is limited to rocks adjacent to pluton contacts. Assimilation of country rock to give a hybrid garnet-bearing tonalite has been observed rarely along the margins of some of the larger early intrusives. The biotite and garnet of such hybrid rocks are very Fe-rich (Mg/(Mg+Fe) < 0.15), and the rocks show anomalous trace element abundances as well; such rocks are also easily distinguished in the field.

Strontium isotope data for five igneous rock samples from the San Jacinto Mountains [Early and Silver, 1973; Kistler et al., 1973 L.T. Silver unpublished data, 198_]) available at the beginning of the present study showed that a considerable variation in Sr_i (0.7060-0.7075) existed within the mid-Cretaceous intrusives of this relatively small area. Geological mapping shows that these samples are from five different intrusive masses. These prior data defined both the approximate range of Sr_i values and the general similarity of Sr_i variation within the San Jacinto Mountains to that of the Peninsular Ranges batholith as a whole [Early and Silver, 1973; Silver and Early, 1977; Silver et al., 1979]. That work had shown that for the northern 600 km of the batholith, Sr_i in rocks unaffected by hydrothermal systems increases systematically eastward from values as low as 0.703 in some western rocks to values of 0.708 in the desert ranges on the northeast.

Sampling Procedures and Experimental Technique

A principal aim of this study was to identify and delineate any variations in the calculated initial isotopic composition of strontium (Sr_i) within individual intrusive units and to attempt to explain the origin of such variations. Sampling was therefore conducted with several goals in mind: to provide geographic coverage; to provide a representative suite of the major rock types of the plutons; and, in a few cases, to provide an internal check of the method adopted for determining Sr_i. A number of samples were collected adjacent to metamorphic country rocks in order to determine if contamination effects resulting from intrusion-wall-rock interactions were detectable.

Access to fresh rock generally was not a problem. Lower elevations within the study area are well served by roads, while at higher elevations a network of hiking trails provides ready access to most locations. Blasting has been common in the construction of both roads and trails, and samples were collected from blasted material where possible.

From 1 to 10 kg of fresh rock were collected at each site. Approximately 500 g of randomly selected chips were ground to a fine powder in a tungsten-carbide-lined Spex "shatterbox." For most samples, a 50-100 g aliquot was ground for an additional 12 min, and 50-80 mg of this fine powder were then utilized in the Rb-Sr analysis. Rb and Sr concentrations and Sr isotopic composition were measured by standard isotope-dilution mass spectrometry. An aliquot of sample was weighed into a cleaned teflon beaker, spiked with the requisite amount of ^{84}Sr and ^{85}Rb, and digested in HF-$HClO_4$. Rb and Sr were separated by cation exchange, with the Sr fraction processed twice to ensure complete separation from Rb. Both Rb and Sr were loaded as chlorides onto the side filaments of Re triple filament assemblies. The mass spectrometer is a 60° sector, 30-cm radius of curvature, single-focus type constructed at the California Institute of Technology [Wasserburg et al., 1969]. Within-run precision on the strontium isotopic composition was usually better than ±0.00007 ($2\sigma_{mean}$). The precision of a Rb/Sr determination is estimated to be ±1%. All $^{87}Sr/^{86}Sr$ data are normalized to a $^{86}Sr/^{88}Sr$ value of 0.1194 and referenced to a $^{87}Sr/^{86}Sr$ value of 0.70800 for the Eimer and Armend $SrCO_3$ standard.

Sr_i was calculated utilizing the U-Pb age of each pluton obtained from U-Pb isotope studies of zircons (L.T. Silver et al., manuscript in preparation).

Strontium Isotopic Results

Rb and Sr concentrations, $^{87}Rb/^{86}Sr$, measured $^{87}Sr/^{86}Sr$, and calculated initial $^{87}Sr/^{86}Sr$ (Sr_i) for 76 representative igneous rocks and six inclusions from the northwestern San Jacinto Mountains are presented in Tables 1a and 1b. Locations of analyzed samples are shown on the geological map (Figure 1). In addition, garnet-bearing tonalites interpreted as hybrid rocks from their field relations have been analyzed to examine the effects of high-level incorporation of metasedimentary material into tonalitic magma. Analytical data for five such rocks are presented in Table 2.

Analyzed samples of rocks from the early intrusives span the compositional range olivine gabbro through granite. Sr_i for apparently unexchanged samples varies from 0.7057 to 0.7078. Samples of tonalite and K-feldspar-poor granodiorite from the large intrusive units show similar ranges of Sr_i. Within unit I, Sr_i varies from 0.7060-0.7077; within unit II the range is 0.7058-0.7074; and for unit III it is 0.7058-0.7073.

A principal aim of this study was to document and interpret any variations in primary Sr_i. By primary Sr_i we mean the $^{87}Sr/^{86}Sr$ of a sample at the time of crystallization. Because various processes are capable of modifying Rb, Sr, and $^{87}Sr/^{86}Sr$ of a rock subsequent to crystallization, their possible effects are examined prior to discussion of inferred primary Sr_i.

Intrusive-Wall Rock Interaction

The primary $^{87}Sr/^{86}Sr$ ratio of an igneous rock may be modified by interaction with wall rocks during or after crystallization. Alternatively, the $^{87}Sr/^{86}Sr$ ratio at the time of crystallization may itself be in part the end result of interactive exchange during magma transport. Assimilation or exchange with country rocks can substantially alter the isotopic properties of igneous bodies [e.g., Taylor, 1971, 1980; DePaolo, 1981b]. The paucity of inherited zircon in the many tonalites analyzed indicates that the amount of wall rock assimilated was negligible (L.T. Silver et al., manuscript in preparation). The consistency of Sr_i patterns, at the batholith scale and within individual plutons irrespective of host rocks, implies that there was little contamination by host rock strontium. This observation holds for the batholith in general [Early and Silver, 1973], as well as for the San Jacinto Mountains intrusives. However, Sr exchange is apparent for two samples (213,297) from within 100 m or so of the metasedimentary wall rocks of the northwestern marginal zone of unit III. They show textural features (chloritization of biotite, development of substantial turbidity of feldspar) indicative of interaction with hydrothermal fluids. A dyke rock (211) intrusive into metasedimentary roof rocks in this area has similar textural features and is also thought to have acquired radiogenic strontium during interaction with these host materials. These three samples are the only samples from the major tonalitic units for which persuasive a priori evidence for interaction with the host rocks exists. The effects of limited exchange with a circulating hydrothermal fluid, however, may be difficult or impossible to distinguish by field or petrographic criteria alone [e.g., Taylor and Forester, 1979]. Oxygen isotope data for several tonalites and low-K granodiorites adjacent to contacts with metasedimentary rocks are interpreted as showing evidence for minor exchange between the oxygen of the igneous rocks and a circulating hydrothermal fluid buffered by the oxygen reservoir of metasedimentary wall rocks [Hill et al., 1986]. Strontium exchange effects cannot be distinguished with certainty for such samples, either because of low

TABLE 1A. Igneous Country Rocks

	Sample Number	Rock Type	Measured Rb	Measured Sr	Measured $^{87}Rb/^{86}Sr$	Measured $^{87}Sr/^{86}Sr$	Calculated $^{87}Sr/^{86}Sr$ at 94 m.y.
		Northwestern San Jacinto Mountains					
Tonalite of Lamb Canyon	LTS153	Bi-hb-tn ton.	35.4	676.1	0.151	0.70593 ± 6	0.70573
Granodiorite of Poppet Creek	LTS114	Fol. bi-hb grd.					0.70573
	LTS317	Fol. bi-hb grd.	98.1	283.5	1.002	0.70787 ± 4	0.70668
Unnamed sill south of Banning	LTS211	Fol. bi ton.	68.8	579.4	0.383	0.70857 ± 4	0.70806
		Northern San Jacinto Mountains					
Tonalite of Snow Creek	LTS35	Fol. bi-hb-tn ton.	57.9	602.9	0.278	0.70804 ± 8	0.70767
	LTS302	Fol. bi-hb-tn ton.	61.8	612.0	0.292	0.70828 ± 6	0.70789
		Thomas Mountain					
Tonalite of Lucky Deer Mine	LTS381	Bi-hb ton.	49.7	632.7	0.227	0.70644 ± 6	0.70614
Unnamed dike	LTS382	Fol. granite dike	93.7	138.6	1.956	0.70840 ± 6	0.70579
Olivine gabbro	LTS27	Calcic gabbro					
		Garner Valley and Desert Divide					
Granodiorite of Apple Canyon	LTS315	K-fs megacrystic grd.	119.7	227.2	1.525	0.79872 ± 6	0.70668
Tonalite of Herkey Creek	LTS316	Bi-hb-tn ton.	53.0	538.2	0.285	0.70673 ± 8	0.70635
Penrod "Quartz Monzonite"	LTS318	Fol. bi-gar-(sill) gr.	171.0	78.3	6.328	0.72050 ± 10	0.71205
		High Plateau of San Jacinto Mountain southeast of San Jacinto Peak					
Unnamed igneous rocks from	LTS293	Bi ton.	107.7	266.8	1.168	0.70850 ± 9	0.70694
northeast of Idylwild	LTS314	Fol. bi-hb ton.	80.0	461.7	0.501	0.70746 ± 4	0.70679

Bi, biotite; hb, hornblende; ton, tonalite; tn, titanite; Fol, foliated; grd, granodiorite; gar, garnet; gr, granite

TABLE 1b Major Tonalitic Units

Sample Number	Rock Type	Measured				Calculated
		Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$^{87}Sr/^{86}Sr$ at 94 m.y.
			Unit 1			
LTS147	Bi-hb-tn ton.	64.4	594.9	0.313	0.70804 ± 8	0.70762
LTS150	Bi-hb-tn ton.	73.8	559.8	0.381	0.70754 ± 4	0.70703
LTS215	Bi-hb-tn ton.	63.1	581.6	0.314	0.70782 ± 11	0.70740
LTS216	mafic zenolith	118.8	578.4,	0.595	0.70818 ± 7	0.70739
LTS217	Bi-hb-tn ton.	92.4	495.4	0.540	0.70803 ± 5	0.70731
LTS218	Bi-hb-tn low-K grd.	90.4	513.5	0.509	0.70701 ± 3	0.70733
LTS219	Bi-hb-tn ton.	86.5	513.5	0.488	0.70793 ± 3	0.70728
LTS220	Bi-hb-tn ton.	60.8	617.6	0.285	0.70778 ± 6	0.70740
LTS298	Bi-hb-tn lwo-K grd.	73.5	510.5	0.417	0.70755 ± 7	0.70699
LTS299	Bi-hb-tn ton.	71.9	499.5	0.417	0.70769 ± 8	0.70713
LTS300	Bi-hb-tn ton.	83.6	558.2	0.434	0.70757 ± 8	0.70699
LTS301	Bi-hb-tn ton.	78.0	491.9	0.459	0.70778 ± 7	0.70717
LTS319	Bi-hb-tn ton.	56.5	598.7	0.273	0.70744 ± 5	0.70708
LTS320	mafic zenolith	48.0	98.5	0.279	0.70748 ± 6	0.70711
LTS321	Bi-hb-tn ton.	82.5	560.2	0.426	0.70758 ± 8	0.70701
LTS322	bi grd.	95.3	429.8	0.642	0.70777 ± 10	0.70691
LTS323	Bi-hb-tn ton.	57.7	575.9	0.290	0.70732 ± 4	0.70693
LTS324	Bi-hb-tn ton.	48.3	615.4	0.227	0.70654 ± 5	0.70624
LTS325	Bi-hb-tn ton.	49.0	580.1	0.244	0.70654 ± 3	0.70621
LTS330	Bi-hb-tn ton.	63.9	575.7	0.321	0.70789 ±3	0.70746
LTS361	Bi-hb-tn ton.	98.5	490.2	0.581	0.70786 ± 3	0.70708
LTS362	Bi-hb-tn ton.	56.2	538.9	0.302	0.70715 ± 4	0.70675
LTS363	Bi-hb-tn ton.	51.0	546.9	0.270	0.70718 ± 6	0.70682
LTS372	Bi-hb-tn ton.	52.0	583.7	0.258	0.70640 ± 6	0.70606
			Unit II			
LTS148	Bi-hb-tn ton.	50.9	620.1	0.237	0.70737 ± 6	0.70705
LTS149	Bi-hb-tn ton.	84.3	459.8	0.531	0.70762 ± 8	0.70696
LTS287	Bi-hb-tn ton.	73.3	489.2	0.426	0.70776 ± 6	0.70719
LTS288	Bi-hb-tn ton.	96.8	500.9	0.559	0.70778 ± 5	0.70703
LTS289	Bi-hb-tn ton.	71.5	510.2	0.405	0.70796 ± 8	0.70742
LTS326	Bi-hb-tn ton.	93.7	533.0	0.509	0.70814 ± 4	0.70746
LTS327	Bi-hb-tn ton.	87.3	406.9	0.621	0.70815 ± 3	0.70732
LTS328	Bi-hb-tn ton.	78.9	463.8	0.492	0.70788 ± 4	0.70722
LTS329	Bi-hb-tn ton.	47.9	599.6	0.231	0.70635 ± 4	0.70604
LTS368	Bi-hb-tn ton.	63.9	573.3	0.323	0.70744 ± 4	0.70701
			Unit III			
LTS145	Bi-hb-tn ton.	73.1	510.6	0.414	0.70717 ± 8	0.70662
LTS146	Bi-hb-tn ton.	70.4	541.8	0.376	0.70734 ± 6	0.70684
LTS151	Bi-hb-tn ton.	74.1	540.3	0.397	0.70729 ± 6	0.70676
LTS152	Bi-hb-tn ton.	72.6	542.6	0.387	0.70721 ± 5	0.70669
LTS212	Bi-hb-tn grd.	84.8	477.2	0.514	0.70760 ± 5	0.70691
LTS213	Bi-tn grd.	87.4	551.3	0.459	0.70696 ± 7	0.70635
LTS221	Bi-hb-tn ton.	80.4	425.8	0.546	0.70797 ± 6	0.70724
LTS222	Bi-hb ton.	75.4	538.5	0.405	0.70717 ± 11	0.70663
LTS290	Bi-hb-tn ton.	82.3	571.1	0.417	0.70753 ± 4	0.70697
LTS291	Mafic xenolith	66.2	580.2	0.330	0.70740 ± 4	0.70696
LTS292	Bi-hb-tn grd.	71.5	494.2	0.419	0.70787 ± 5	0.70729
LTS297	Fol. fine gr. bi grd.	100.2	479.5	0.605	0.70808 ± 4	0.70727
LTS331	Bi-hb-tn ton.	70.3	539.6	0.377	0.70700 ± 4	0.70650
LTS332	Bi-hb-tn ton.	85.4	514.2	0.481	0.70758 ± 4	0.70694
LTS333	Bi-hb-tn ton.	69.3	529.9	0.379	0.70740 ± 3	0.70689
LTS334	Bi-hb-tn ton.	70.9	543.9	0.377	0.70733 ± 4	0.70683
LTS335	Bi-hb-tn ton.	66.4	568.3	0.338	0.70702 ± 3	0.70657
LTS336	Bi-hb-tn ton.	69.7	588.4	0.342	0.70631 ± 5	0.70585
LTS337	Bi-hb-tn ton.	68.9	552.1	0.361	0.70709 ± 5	0.70661
LTS358	Bi-hb-tn low-K grd.	81.6	517.4	0.457	0.70775 ± 4	0.70714
LTS359	Bi-hb-tn ton.	61.8	543.0	0.329	0.70733 ± 4	0.70689

TABLE 1b. (continued)

Sample Number	Rock Type	Measured Rb	Measured Sr	Measured $^{87}Rb/^{86}Sr$	Measured $^{87}Sr/^{86}Sr$	Calculated $^{87}Sr/^{86}Sr$ at 94 m.y.
		Unit III (continued)				
LTS360	Bi-hb-tn ton.	76.3	576.9	0.383	0.70747 ± 4	0.70696
LTS365	Bi-hb-tn ton.	82.9	438.8	0.546	0.70779 ± 5	0.70706
LTS366	Bi-hb-tn low-K grd.	106.1	470.2	0.653	0.70757 ± 3	0.70670
LTS367	Bi-hb-tn low-K grd.	76.9	478.2	0.465	0.70738 ± 4	0.70676
LTS369	Bi-hb-tn ton.	98.3	497.4	0.572	0.70758 ± 3	0.70682
LTS370	Bi-hb-tn ton.	76.3	547.1	0.403	0.70720 ± 5	0.70666
LTS371	Bi-hb-tn ton.	64.6	538.9	0.348	0.70729 ± 6	0.70683
LTS373	Bi-hb-tn ton.	81.8	556.4	0.425	0.70659 ± 2	0.70602
LTS374	Bi-hb-tn ton.	84.7	513.4	0.478	0.70772 ± 4	0.70708
LTS375	Bi-hb-tn ton.	85.1	486.8	0.506	0.70779 ± 3	0.70711
LTS376	Bi-hb-tn ton.	82.8	561.0	0.427	0.70728 ± 6	0.70671
LTS377	Mafic xenolith	70.0	670.6	0.302	0.70761 ± 4	0.70721
LTS378	Mafic xenolith	73.9	651.7	0.328	0.70771 ± 5	0.70727
LTS379	Mafic xenolith	78.5	481.7	0.471	0.70744 ± 5	0.70681
		Mafic Dike Intrusive Into Unit III				
LTS214	Mafic dike	44.0	786.9	0.162	0.70861 ± 4	0.70839

See Table 1a footnote.

water-rock ratios or low Sr concentrations in the exchanging fluids.

Five samples of igneous rock contaminated with metasedimentary materials show increased Sr_i (Table 2). Values of Sr_i for these samples range from 0.708 to 0.713 compared to an inferred uncontaminated value of 0.7068 or less.

Although considerably more felsic than the samples listed in Table 2, a sample from the granite of Penrod Canyon (318) shows both petrographic and oxygen isotopic evidence for considerable interaction with the host metasedimentary rocks. Oxygen isotope data suggest that this interaction may have taken place with a circulating hydrothermal fluid largely buffered in composition by these metasedimentary rocks [Hill et al., 1986]. The apparently high Sr_i (0.7121) calculated for this pluton (Table 1) is thus interpreted to have resulted from subsolidus exchange processes.

It thus appears that incorporation or exchange with wall rock Sr can be detected in only a few samples, was a relatively minor effect, and was largely restricted to rocks for which there is independent evidence of such processes. We conclude that for the vast majority of analyzed samples, pluton-wall rock interactions were of negligible importance.

Possible Sources of Error in the Calculation of Sr_i

The young age and low Rb/Sr of these rocks make calculation of Sr_i relatively insensitive to errors in either age or Rb/Sr determinations. For a typical rock, with $^{87}Rb/^{86}Sr = 0.4$, a 5% error in measurement of this ratio contributes an error of less than ±0.00003 to the calculated initial $^{87}Sr/^{86}Sr$ ratio. A 5% error in the age determination would contribute a similar but systematic error in calculated Sr_i. The main uncertainty in Sr_i determination is thus, for most samples, the within- and between-run mass spectrometric uncertainty, which is generally less than ±0.00007.

Rock samples having a range in compositions were collected from a limited interval (few hundred meters) along State Route 243 south of Idyllwild (217,218,219). With a range in color index between 13.2 and 18.1 a range in $^{87}Rb/^{86}Sr$ was anticipated, allowing a check on whether calculated Sr_i was independent of Rb/Sr. Although a smaller range in $^{87}Rb/^{86}Sr$ than expected was present (0.488-0.540), the calculated initial ratios, assuming a 94 m.y. age, were 0.70731 ± 5, 0.70733 ± 3 and 0.70728 ± 3, agreeing within analytical uncertainties. These data argue in favor of closed-system behavior of Rb and Sr at the scale of a typical sample (approximately a liter).

Geographic Variation in Sr_i

The geographic distribution of calculated Sr_i for all analyzed igneous rock samples excepting the granite of Penrod Canyon and the contaminated samples from Red Tahquitz, is shown on Figure 2.

A more detailed analysis of Sr_i as a function of geographic location is shown in Figure 3. It is clear that there are significant variations in Sr_i within the igneous rocks of the northwest San Jacinto Mountains and that these variations are strongly correlated with position.

Data for uncontaminated igneous country rocks are plotted on Figure 3a. Most of these bodies are of small size; the largest have dimensions of a few kilometers. The consistent northeastward increase in Sr_i displayed by these samples is striking and is entirely consistent with the pattern demonstrated for the rest of the batholith

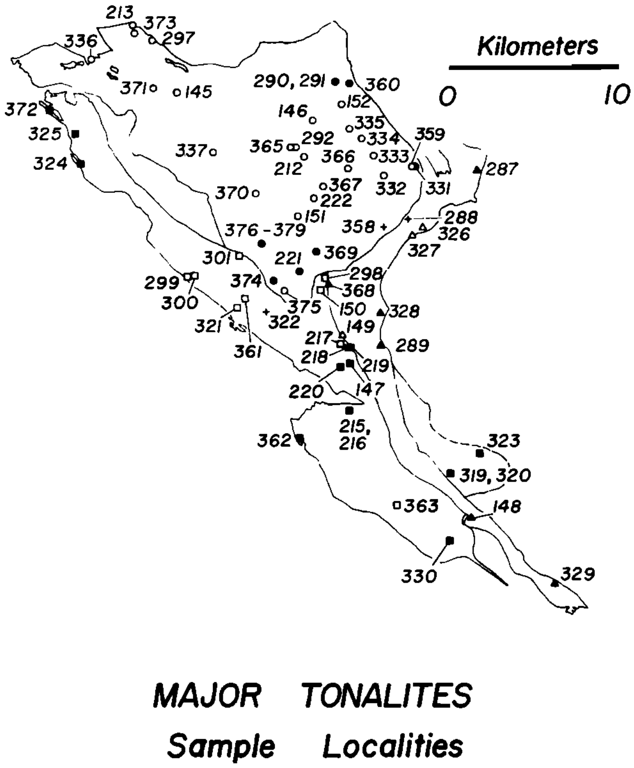

Fig. 1. Simplified geological map of the San Jacinto Mountains showing sample localities. Open symbols, rocks with >65.5 wt % SiO_2; solid symbols, rocks with <65.5 wt % SiO_2. Squares, unit I; triangles, unit II; circles, unit III; plus signs, felsic differentiates; asterisks, dyke rocks; diamonds, early intrusives; stars, metasedimentary rocks.

by other workers [Early and Silver, 1973; Silver et al., 1975; Silver and Early, 1977; L.T. Silver, unpublished data, 198_]. These samples range over almost the entire compositional field of igneous rocks, from olivine gabbro to true granite. For all samples it appears that Sr_i is determined solely by position. This consistent west-to-east pattern is interpreted as being dominantly, if not completely, inherited from similar variations in the source regions (presumed to be in the mantle or lower crust). The consistency of this regional pattern, regardless of pluton size and composition and of the age and nature of wall rocks, limits any substantial component of horizontal transport normal to the axes of the batholith during movement of these magmas through the crust. If transport was largely accomplished by moving material through cracks (dykes), as is suggested by field relationships within the San Jacinto Mountains, then orientation of dykes parallel to source variations will not blur the source patterns within the high-level rocks. The long axes of the larger plutons within the San Jacinto Mountains are commonly oriented approximately parallel to the long axis of the batholith and to the asymmetric isotope and trace element variations. Estimates of the importance of horizontal transport parallel to the long axes of such bodies cannot be constrained by the isotope data. However, the isotope data from the early intrusives appear to limit transport normal to the batholith axis to at most a few kilometers.

Figure 3b shows the geographic distribution of Sr_i within unit I, the oldest of the main tonalite bodies. Although sample coverage is somewhat limited, it is clear that this unit contains rocks with substantially different Sr_i (0.7060-0.7076) and that this variation is not completely random. Rather, a ridge of high values in the central-southeastern portion of the pluton gives way to lower values in all directions. Highs along this ridge are spaced 10-12 km apart. Sr_i for this pluton is to the high side of values expected from its geographic position (0.7055-0.7065; cf. Figure 3a).

Data for unit II are somewhat limited. However, a range in Sr_i is apparent, and Sr_i increases from west to east across this pluton (Figure 3c). Again, the pattern of Sr_i cuts across the trend of the batholithic variation.

Unit III shows the most complex pattern of geographic distribution of Sr_i (Figure 3d). The western portion of the pluton shows an apparent regular increase in Sr_i northeastward. This variation, which follows the batholith pattern, is replaced in the central and eastern part of the pluton by a pattern of highs and lows that is apparently related to geographic position only and is not obviously influenced by elevation, rock type, or distance from contacts. Samples with similar Sr_i come from a wide range of elevations (over 900 m), while adjacent samples at comparable elevations may have quite different Sr_i.

Variation in Sr_i does not appear to correlate with any measured petrological or geochemical parameter other than geographic position. This lack of covariation of Sr_i with any other measured petrological, geochemical, or isotopic parameter is best illustrated by data from unit III (Figure 4) where the geographic regularity of other parameters is so striking but also appears to be a feature of all other igneous rock units

TABLE 2. Contaminated Rocks, Red Tahquitz Area

Sample Number	Rock Type	Measured Rb	Sr	$^{87}Sr/^{86}Sr$	$^{87}Sr/^{86}Sr$	Calculated Sr_I at 97 m.y
LTS271	Gar-bearing bi-all ton.	77.1	322.2	0.692	0.70814 ± 5	0.70722
LTS311	Fol. bi-hb-all ton.	54.5	286.5	0.550	0.71265 ± 3	0.71192
LTS380	Fol. bi-hb-all ton.	39.5	311.5	0.367	0.70806 ± 3	0.70757
LTS383	Gar bearing bi-all ton.	56.0	254.4	0.637	0.70984 ± 3	0.70899
LTS384	Gar bearing bi-all ton.	63.1	279.7	0.652	0.70801 ± 7	0.70714

Gar, garnet; bi, biotite; all, allanite; Fol., foliated; ton., tonalite; hb, hornblende.

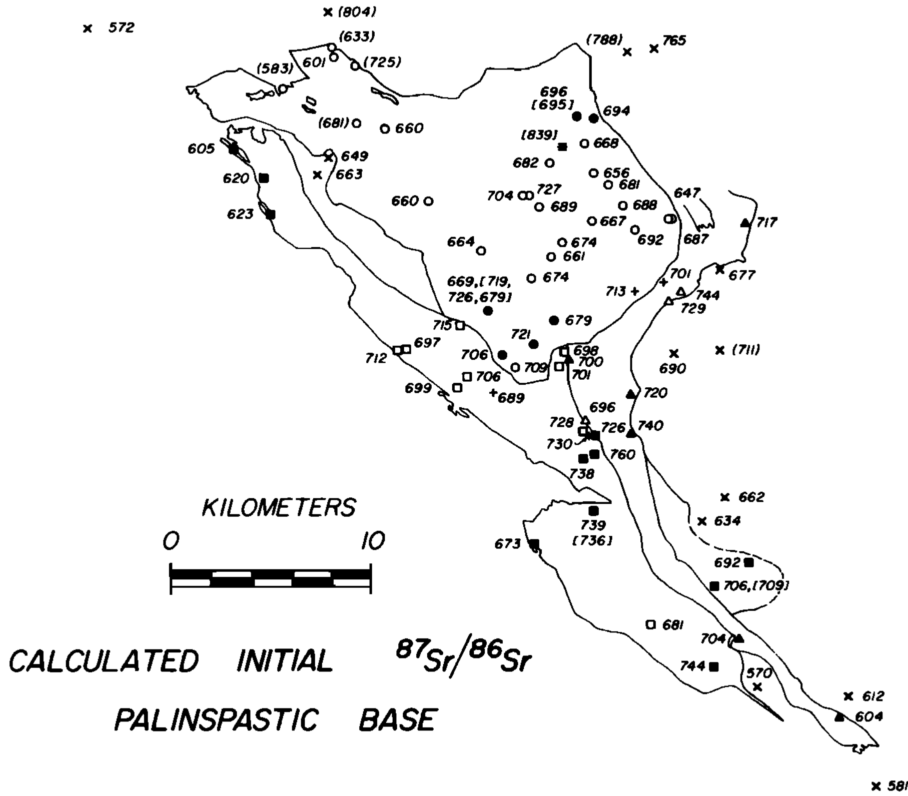

Fig. 2. Calculated initial $^{87}Sr/^{86}Sr$ for igneous rocks from the San Jacinto Mountains. Palinspastic base from Hill [1984]. Numbers shown are last three digits of a five-figure ratio. Symbols as for Figure 1.

of the San Jacinto Mountains. This implies that for this region, there must be significant decoupling of the processes responsible for Sr isotopic properties from those responsible for other petrologic characteristics. The demonstration of substantial variation in Sr_i at the scale of a kilometer or less provides a strong constraint on the scale of convective processes operating within these magma chambers.

Calculated Sr_i for analyzed mafic inclusions ranges from 0.7068 to 0.7074, within the range of values shown by the tonalites. A single analysis of a mafic dyke-rock (214) yields an Sr_i of 0.7084; a tonalitic dyke-rock (221) has Sr_i = 0.7072. Four inclusions (including one cognate inclusion) have Sr_i indistinguishable from that of their host tonalite; two do not. The Sr_i of the mafic dyke (0.7084) is much higher than that of its host tonalite (0.7066-0.7070); Sr_i of the tonalitic dyke rock (0.7072) is only slightly higher than that of surrounding tonalites (0.7067-0.7071). The inclusions have been interpreted as samples of liquid added to the inflating magma chambers [Hill, this issue]. The heterogeneity in Sr_i shown by liquids from these inferred feeders thus supports the proposition that liquids being added to the magma chambers at different times and places had different Sr_i. There is a weak suggestion in the data that the later liquids added to each chamber had higher $^{87}Sr/^{86}Sr$ ratios. This is inferred from the central belt of high Sr_i within unit I and from the high Sr_i of the dyke intruding unit III. This apparent change in Sr_i with time may reflect depth-related variation within the source region, just as the change in Sr_i with position is inferred to reflect lateral variation within this source.

Discussion

The data presented above demonstrate considerable strontium isotope heterogeneity within three large tonalite plutons of the northern Peninsular Ranges batholith. These variations result from incomplete homogenization of batches of isotopically variable liquids derived from an isotopically heterogeneous source. Combined strontium and oxygen data [Hill et al., 1986] require a minimum of three isotopically distinct components in the generation of these magmas. Mixture of two of these end-member compositions, inferred to be derived from the upper mantle or subducted oceanic crust and from geosynclinal sediments or marine volcanic rocks altered at low temperatures, gives the Sr-O trend described for the main part of the batholith [Taylor and Silver, 1978]; the third component, possibly derived from old continental lithosphere, is recognized not only in the San Jacinto rocks but also in Cretaceous batholithic rocks of the Mojave block and the Sierra Nevada [Hill et al., 1986]. The presence of this third component complicates interpretation of the San Jacinto isotope data.

The observed isotope variations in the San Jacinto rocks could be produced by any one, or a combination of, three processes: (1) rapid crystallization of heterogeneous hot liquids upon emplacement into relatively cool magma chambers to yield heterogeneous solid products, (2) in-

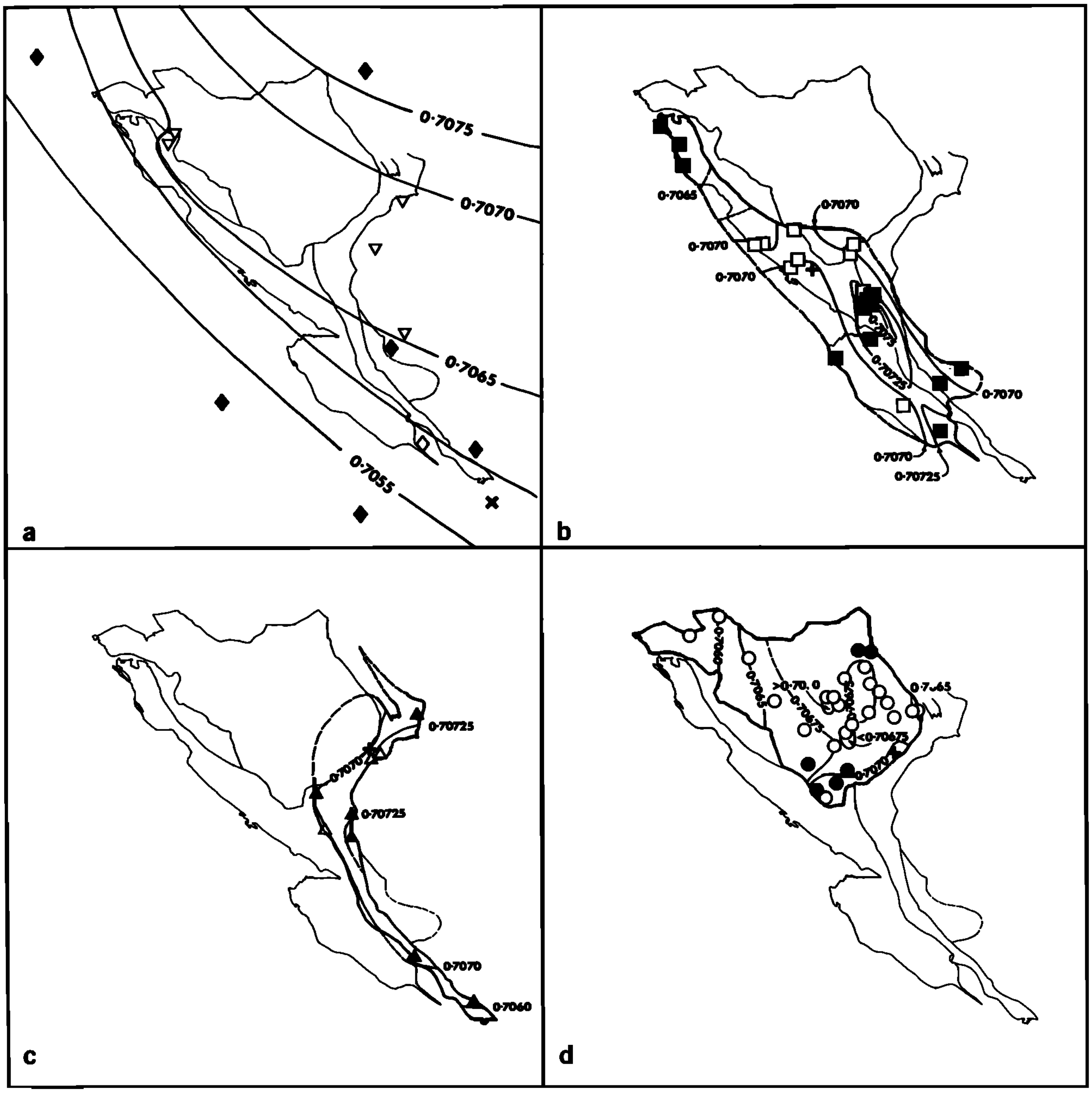

Fig. 3. Summary of calculated initial $^{87}Sr/^{86}Sr$ (Sr_i) for uncontaminated, unexchanged San Jacinto igneous rocks. Palinspastic base from Hill [1984]. Data from Table 1 and from R.I. Hill and L.T. Silver (unpublished data, 198_). (a) Early intrusives. Cross, olivine gabbro; solid diamonds, tonalites; open inverted triangles, granodiorites; open diamond, granite. Consistent trend of increasing Sr_i northeastward is consistent with trend reported for the northern 600 km of the PRB reported by Early and Silver [1973] and is independent of rock type. (b) Unit I. Symbols as for Figure 1. (c) Unit II. Symbols as for Figure 1. (c) Unit III. Symbols as for Figure 1.

complete mixing of batches of heterogeneous liquids, (3) modification of initial isotopic composition by variable reaction with later isotopically distinct percolating fluids.

Forced crystallization of liquids upon entering the magma chamber has been argued to be an important process in the development of both geochemical and oxygen isotope variation within the more mafic tonalites [Hill et al., 1986, this issue]. However, both the geochemical and oxygen isotope characteristics of the more felsic rocks appear to require substantial mixing of these heterogeneous liquids in order to produce the large volumes of relatively homogeneous felsic tonalite and K-feldspar-poor granodiorite. As with oxygen, Sr_i in the mafic tonalites shows a much larger range (from 0.7058 to 0.7076) than does Sr_i in the most felsic tonalites and K-feldspar-poor granodiorites (Figure 5). The implication is that the more felsic rocks crystal-

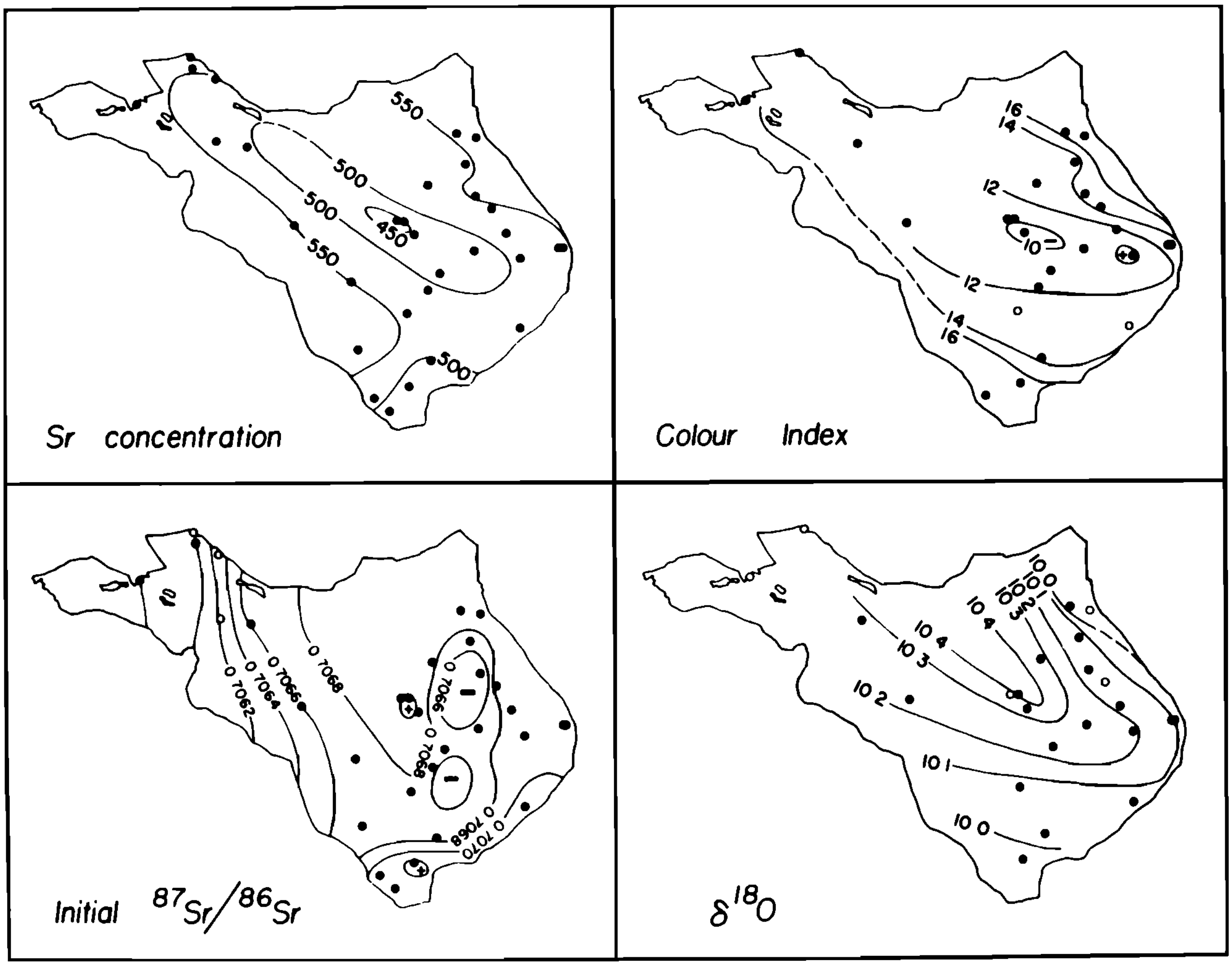

Fig. 4. Summary of petrographic, geochemical and isotopic data for unit III illustrating lack of correlation of Sr_i with other observed parameters. Color index data from Hill [this issue]; $\delta^{18}O$ data from Hill et al. [1986].

lized from liquids that had been relatively well blended within the magma chambers or felsic liquids derived from a more uniform source. The geochemical evidence that the most felsic rocks crystallized from liquids that had evolved by removal of early mafic phases within the magma chambers [Hill et al., this issue] argues strongly for blending of initially heterogeneous liquids within these magma chambers and against derivation from a uniform source.

In the San Jacinto situation it is difficult to argue against modification of an early pattern of homogeneous Sr_i by late introduction of either variable amounts of, or isotopically heterogeneous, later liquids that infiltrate the void spaces of a crystal mush. The isotope data for the dyke rocks and inclusions demonstrate that such isotopically variable but chemically similar liquids were available late in the solidification histories of the various plutons. Elsewhere in the batholith the strontium isotope pattern is controlled by regular west-to-east variation in source composition [Early and Silver, 1973; Silver et al., 1979]. Production of this pattern by late addition of an infiltrating component requires a particularly fortuitous set of circumstances operating over a range of rock chemistries and solidification histories and over distances of hundreds of kilometers. Such a process may be responsible for some modification of initial isotopic patterns but is thought to be largely insignificant in the generation of the large variations seen in the batholith. By analogy, late-stage modification is considered to be unimportant for the San Jacinto rocks as well.

We now consider the likely effects of convection within the magma chambers and the implications of the isotope data for the nature and scale of convective processes. If isotope variations related to late-stage modification are dismissed as unimportant, we are left with a picture of a magma chamber crystallizing heterogeneous solids upon addition of each new pulse of magma. Residual liquids from such additions are added intermittently to a growing volume of more fractionated liquid within the magma chamber. In this model, there may be considerable, but incomplete, homogenization within this volume of evolving liquid.

Both theoretical analysis and experimental studies [e.g., Shaw, 1965; Bartlett, 1969; Huppert and Sparks, 1984; Sparks et al., 1984] indicate that bodies of silicate liquid with dimensions of kilometers and compositions as SiO_2-

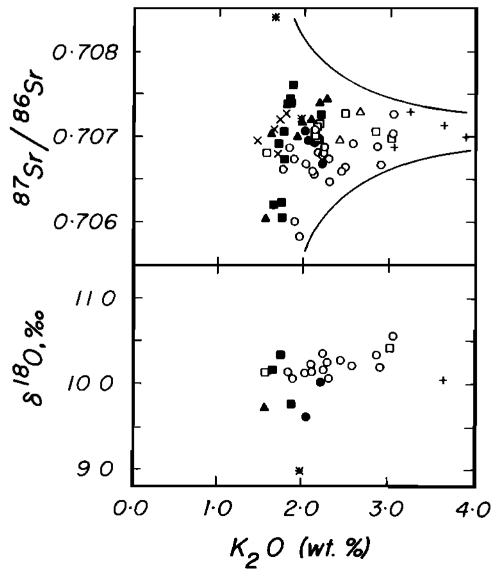

Fig. 5. Sr_i and $\delta^{18}O$ versus K_2O. The more mafic rocks have much more variable Sr_i and $\delta^{18}O$ than do the felsic rocks; this is interpreted as resulting from precipitation of the more felsic rocks from liquids with longer mean residence time in the magma chambers, allowing more time for mixing of batches of initially heterogeneous liquids. The trend to higher $\delta^{18}O$ at increasing K_2O results from variation in mineral proportions [Hill et al., 1986]. Symbols as for Figure 1; data sources as for Figure 4.

rich as rhyolite may at times be in vigorous turbulent convection. By these arguments, relatively fluid magmas such as those inferred to have existed within the San Jacinto magma chambers [Hill et at., this issue] would almost certainly have been convecting vigorously throughout part of their histories. If these convective systems operated at the scale of the entire magma volume, rapid and complete homogenization of any variations within the chamber would be expected [e.g., Huppert and Sparks, 1984]. The presence of isotope heterogeneities within these plutons thus argues strongly that convection must have operated at a less-than-whole pluton scale.

Solidification of the plutons proceeded inward (and, for much of units II and III, upward) from the nonvertical pluton walls. No extensive felsic cap formed beneath the roof of any of the plutons; either no such cap accumulated, or, if it did, it was removed, perhaps by eruption. The formation of an uppermost fractionated layer has been studied experimentally [McBirney, 1980; McBirney et al., 1985; Turner, 1980]; these studies suggest that upward percolation of relatively low-density fractionated liquids generated by sidewall crystallization on a vertical pluton wall can efficiently form an SiO_2-rich layer beneath the pluton roof.

Fractionated liquids produced by solidification on an inward sloping surface will be expected to rise into the overlying, more dense liquid. In a static system (i.e., no convection) these liquids might ultimately rise through the overlying magma to pool under the pluton roof. Within a dynamic system, admixture of parcels of fractionated liquid into the overlying liquid could result in the development of both vertical and horizontal chemical (and density) gradients, which could act to either stabilize or destabilize the system, depending on the magnitude and direction of the induced variations.

Sidewall cooling of an initially chemically and thermally homogeneous liquid commonly results in development of double-diffusive layering. Cooling from the top has similar effects [e.g., Huppert et al., 1982]. It is plausible that the requisite conditions for the development of double-diffusive layering existed for the San Jacinto systems; detailed theoretical analysis of such a possibility is beyond the scope of the current report. Development of thin, horizontally extensive convecting layers by double-diffusive or other processes is consistent with the evidence for both considerable homogenization (within a layer) and maintenance of some heterogeneity (between layers).

Is there any evidence that double-diffusive processes were operating within these systems? The presence of double-diffusively produced layering is compatible with, but is not proven by, the combined geological, geochemical, and isotopic data. Some type of breakup of a convecting system into relatively small (kilometer scale or less) cells is required by the isotope data, and double diffusion provides a plausible mechanism. The dominant subhorizontal plunge of linear features (mineral and inclusion alignment) is suggestive of repeated intervals when fluid flow was dominated by a horizontal component, perhaps implying horizontally extensive but vertically restricted convection cells. The presence of lineations also appears to imply periods of laminar flow adjacent to pluton walls, apparently not in accord with analysis of fluid dynamical conditions within convecting plutons [Sparks et al., 1984].

Some Geological and Geochronological Considerations

Relation of $^{87}Sr/^{86}Sr$ to $^{87}Rb/^{86}Sr$

Figure 6 shows the $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ data for the major tonalites plotted on an isochron diagram. A reference isochron for 94 Ma is shown. Felsic samples, as expected, have higher $^{87}Rb/^{86}Sr$ than do the predominant tonalites. There does appear to be a weak overall tendency for samples with higher $^{87}Rb/^{86}Sr$ to have higher $^{87}Sr/^{86}Sr$. Given the observed Rb and Sr abundances, this effect is much larger than could be expected solely from the accumulation of radiogenic Sr since the time of crystallization. It is obvious from inspection of Figure 6 that use of the total rock method of Rb-Sr dating for these rocks would be fraught with difficulties. One of the fundamental assumptions needed for application of this technique, that the system had homogeneous $^{87}Sr/^{86}Sr$ at the time of crystallization, is invalid. As the isotopic systems evolve, however, the amount of radiogenic strontium accumulated from in situ ^{87}Rb decay becomes large compared to the small $^{87}Sr/^{86}Sr$ variations initially present, and the error introduced by these initial variations becomes progressively less significant. Table 3 lists "ages" calculated for each unit 906 m.y. in the future. The deviation from the true age (1000 m.y.) would then be of the order of 10%, still significant but much less of a problem than is the case today.

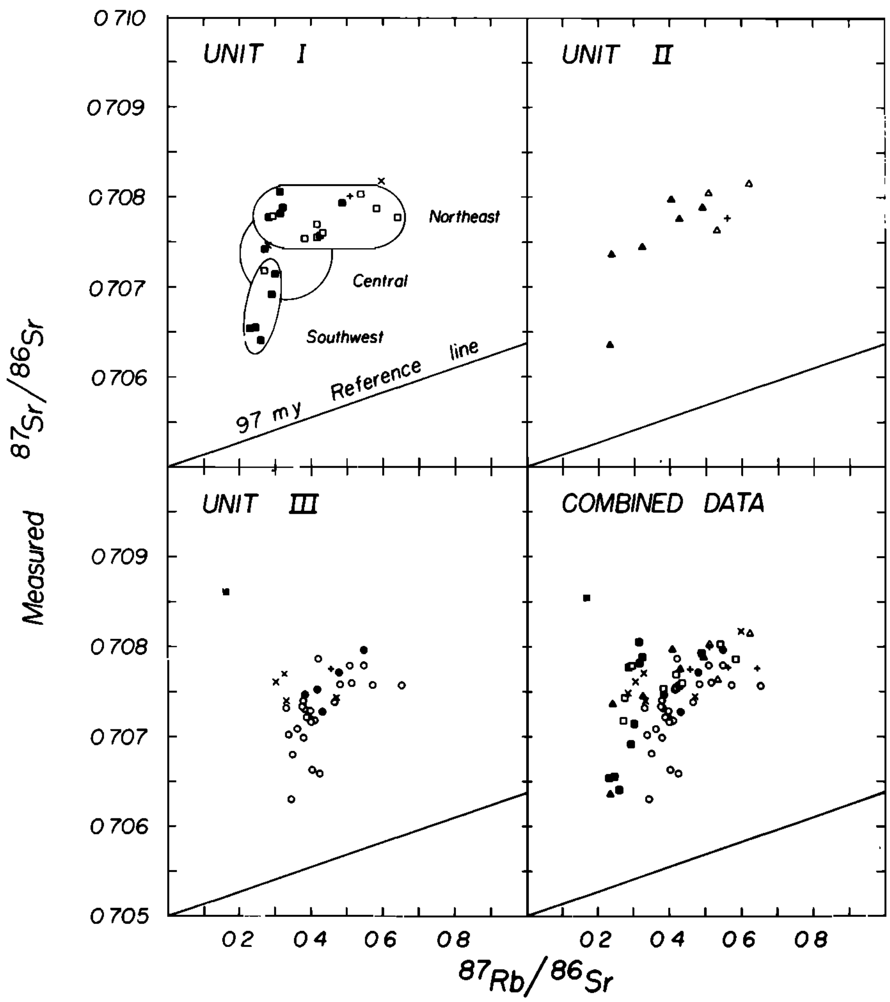

Fig. 6. Isochron diagrams for San Jacinto rocks. The 94 Ma isochron is for reference only.

In the general case of derivation of a pluton from a source dominated by two end-member components, the case for the bulk of the PRB, it is plausible that Sr_i would correlate with Rb/Sr. This appears to have been the case for several of the Murrumbidgee Batholith plutons (including the Clear Range Granodiorite) studied by Roddick and Compston [1977], where a southward decrease in both Rb/Sr and inferred Sr_i is correlated with a change in rock composition. The combined Rb/Sr and $^{87}Sr/^{86}Sr$ data for this pluton were interpreted as inheriting, perhaps in modified form, a metamorphic isochron from metasedimentary source rocks. An alternative interpretation of these data is that the geographically consistent variations in Rb/Sr, $^{87}Sr/^{86}Sr$ and rock composition reflect facies variations within these metasedimentary source rocks. The northern felsic high Rb/Sr and high $^{87}Sr/^{86}Sr$ rocks were derived from a dominantly shale-sandstone facies, whereas the more southerly rocks show increasing involvement of a more mafic-rich, less mature component. If our interpretation is correct, this is a clear case where an attempt at Rb-Sr whole-rock dating of a pluton failed because the isotope systematics were in part inherited from a regularly heterogeneous source.

Comparison of $^{87}Sr/^{86}Sr$ Data From the San Jacinto Mountains With Data From Elsewhere in the Peninsular Ranges Batholith

A major determining factor in the selection of the San Jacinto Mountains as the site for the detailed study reported here was the availability of a large body of data on regional relationships within the PRB [e.g., Early and Silver, 1973; Silver et al., 1979; Taylor and Silver, 1978; L.T. Silver, unpublished data, 198_]. Relationships within this data set [e.g., Taylor and Silver, 1978] and comparison with published data from the Sierra Nevada batholith (SNB) to the north [e.g., Silver, 1982, 1983] suggested that batholithic rocks of the San Jacinto Mountains had some characteristics transitional between those of the bulk of the PRB and the SNB.

Within the PRB, Sr_i increases systematically toward the east-northeast [Early and Silver, 1973; Silver et al., 1979; L.T. Silver, unpublished data,198_]. With the exception of a single sample from a pluton with a complex post-emplacement history, no plutonic rock from the northern PRB west of the Eastern Peninsular Ranges mylonite zone of Sharp [1979] has yielded an Sr_i value >0.706 except for the rocks of the

TABLE 3. Regression Analysis of Rb/Sr and Sr Isotopic Data

	Rb/Sr	Sr	MSWD
	Unit III		
Regressed data	214 ± 109	0.70604 ± 0.00067	35.4
"Aged" data	1161 ± 107	0.70577 ± 0.00064	13.3
	Unit II		
Regressed data	222 ± 126	0.70628 ± 0.00080	48.8
"Aged" data	1157 ± 137	0.70609 ± 0.00078	24.6
	Unit I		
Regressed data	197 ± 99	0.70645 ± 0.00055	58.8
"Aged" data	1166 ± 120	0.70611 ± 0.00061	29.9

Data regresses to give standard isochron age (slope) and intercept. Actual age (zircon U-Pb) is 94 ± 1 m.y. Data "aged" gpt 90 m.y., then regressed. Actual age should be 1000 m.y. MSWD, Mean Standard Weighted Deviation.

San Jacinto Mountains described above [Early and Silver, 1973; R.I. Hill and L.T. Silver, unpublished data, 198_]. Rocks from above (and east of) the mylonite zone commonly have Sr_i values of 0.706 or higher. The mylonite zone is the locus of considerable telescoping within the PRB [Silver, 1983], bringing generally more radiogenic batholithic rocks westward over the generally less radiogenic batholithic rocks of the central and western peninsula. Various geochemical characteristics (higher K, minor inherited zircon) of these upper plate rocks have been interpreted as evidence for involvement of preexisting cratonic material in magma genesis [Taylor and Silver, 1978]. Details of the origin of this presumably more continentward portion of the batholith are beyond the scope of the present study. It is important to note, however, that although the igneous rocks of the San Jacinto Mountains share at least some of the isotopic properties of these upper plate rocks [Hill et al., 1986], they are not in general more K-rich than are tonalites from elsewhere in the central or western batholith, nor do they show more than traces of inheritance in their zircon populations (Silver et al., manuscript in preparation). These observations appear to limit drastically the amount of involvement of old, chemically evolved crustal material (such as intermediate or felsic igneous rocks, or most sediments) in the petrogenesis of the San Jacinto plutons.

Elsewhere along the North American continental margin, tectonic significance has been attached to particular features of patterns of Sr_i. Kistler and Peterman [1973] noted the close correspondence between the nature of the country rock and Sr_i in the plutons of the SNB and concluded that the line Sr_i = 0.706 apparently reflected the boundary between miogeoclinal and eugeoclinal deposition through the late Precambrian and Paleozoic and, by inference the western edge of the North American craton. The line Sr_i = 0.704 marks the easternmost boundary of exposures of ultramafic rocks since interpreted as ophiolitic fragments emplaced along a major crustal boundary or suture [e.g., Saleeby, 1979], implying that igneous rocks with $0.704 < Sr_i < 0.706$ were emplaced through relatively young continental crust and those with $Sr_i < 0.704$ were emplaced through largely oceanic materials. East of the Sr_i = 0.706 line the pattern is more complex, with significant reversals of the apparent trend to generally higher Sr_i continentward. The distance between the Sr_i = 0.704 and Sr_i = 0.706 contours is small (at most a few tens of kilometers), implying that the area underlain by relatively young continental crust is quite narrow. Interpretation of the tectonic evolution of the Sierran foothills has changed significantly since the publication of Kistler and Peterman's paper, with more recent workers suggesting that the foothills may be the site of major tectonic disruption both prior to and during the development of this multigeneration batholith [e.g., Saleeby, 1981; Schweickert, 1981]. Given this apparently complex evolution, caution must be exercised in interpreting the isotope data from the Sierra Nevada batholith.

The orderly eastward increase in Sr_i within the PRB from values of 0.704 or less to values of 0.706 or higher occurs over a distance of some 70 km northeastward from the coast to the southwestern San Jacinto Mountains and apparently over even greater distances farther south, where the mylonite zone disrupts this pattern. These data imply either a continually gradational source or consistent variation in the relative importance of two or more sources over an immense area.

The geographic complexity of the isotopic patterns described above for the San Jacinto Mountains, while indicating the apparent involvement of complex source volumes do not necessarily indicate "crustal contamination." Similar geographic complexity of isotope variation is not known elsewhere in the PRB, although similar detailed studies of individual plutons are well advanced. This implies that the boundary between these two different regions of differing Sr_i behavior (which is approximately coincident with the present position of the much younger San Jacinto Fault zone) is a fundamental geologic feature separating blocks with differing geological evolution prior to development of the PRB. This boundary is also approximately coincident with the southwestern limit of thick quartz-rich metasedimentary sequences of probable late Precambrian or early Paleozoic age [Hill and Silver, 1983], and with the Sr_i = 0.706 contour. The important characteristic of this latter feature is believed to be the change in behaviour in the geographic distribution of Sr_i, not in the absolute value of this parameter.

Conclusions

1. Initial $^{87}Sr/^{86}Sr$ ratios (Sr_i) for plutonic rocks from the San Jacinto Mountains vary from 0.7057 to 0.7084. Three large plutons each show substantial variation in Sr_i (unit I: 0.7060-0.7077; unit II: 0.7058-0.7074; unit III: 0.7058-0.7073), as do samples of dyke rocks and inclusions interpreted as representing liquids added to the magma chambers during solidification.

2. Interaction of the plutonic rocks with metasedimentary country rocks, either by assimilation or via exchange with a hydrothermal fluid appears to be limited to a narrow marginal zone where there is other evidence (field relations, petrographic features) for the action of such processes. Except for these limited volumes of material, the Rb, Sr, and $^{87}Sr/^{86}Sr$ characteristics of the San Jacinto rocks appear to reflect original magmatic properties.

3. Substantial variation in Sr_i exists within each major intrusive unit. These isotopic variations are apparently unrelated to any other petrological or isotopic parameter for which data are available, but are geographically consistent. These data imply that magma collection and transport processes, as well as processes acting within the magma chamber (such as convection) were in combination incapable of completely homogenizing heterogeneities within liquids successively added to these chambers.

4. A model of a periodically recharged, double-diffusive layered magma chamber is consistent with all of the available geological, geochemical, mineralogical, and isotopic data. The combined data do not, however, prove this model.

5. The substantial heterogeneity of initial $^{87}Sr/^{86}Sr$ shown to have existed in these plutons has implications for use of the Rb-Sr whole rock method of dating. However, for these systems the initial variability in $^{87}Sr/^{86}Sr$ eventually becomes small compared to variations in $^{87}Sr/^{86}Sr$ that develop in rocks with different $^{87}Rb/^{86}Sr$ over a period of time. At 10^9 years after crystallization, a Rb-Sr total rock age for each of the San Jacinto bodies would be in error by about 10%.

6. The geographic variation of Sr_i within the igneous rocks of the San Jacinto Mountains differs fundamentally from that observed elsewhere in the Peninsular Ranges batholith, suggesting that an important prebatholithic structure separates the two areas. The coincidence of this boundary inferred from Sr_i characteristics of igneous rocks with the appearance of "anomalous" oxygen isotopic compositions within these rocks and with a major change in the nature of the prebatholithic metasedimentary rocks lends further support to this inference. The combined geological, petrological and isotopic data are most simply explained if this boundary separates blocks with differing geologic evolution prior to development of the Cretaceous batholith.

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